

# Ultra-high energy Neutrinos from Centaurus A and the Auger hot spot

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(Dated: July 25, 2008)

The Pierre Auger collaboration has reported a correlation between Ultra-High Energy Cosmic Rays (UHECR) and nearby Active Galactic Nuclei (AGNs) within  $\sim 75$  Mpc. Two of these events fall within 3 degrees from Centaurus A, the nearest AGN, clearly suggesting that this object is a strong UHECR emitter. Here we pursue this hypothesis and forecast the expected rate of ultra-high energy neutrinos in detectors like IceCube. In our baseline model we find a rate of  $\sim 0.4\text{--}0.6 \text{ yr}^{-1}$  events above a threshold of 100 TeV, the uncertainty of which is mainly related to the poor knowledge of the physical parameters of the source and on the details of the model. This situation will improve with detailed high energy gamma ray measurements of Cen A by the upcoming GLAST satellite. This would make Cen A the first example where the potential of high energy multi-messenger astronomy is finally realized.

PACS numbers: 95.85.Ry, 96.50.S-, 98.54.Cm

The field of UHECR physics has probably taken a major step forward with the recent detection by the Pierre Auger Observatory of a spatial correlation between the highest energy cosmic ray events and nearby AGNs [1]. 20 out of 27 events with energies above  $\simeq 60$  EeV correlate with a nearby AGN within a radius of  $3.1^\circ$ . Furthermore, 5 out of the 7 non-correlating events lie along the galactic plane where the AGN catalogues are incomplete and the largest magnetic deflections are expected.

With such support for the hypothesis that AGNs are the main emitters of UHECRs it is timely to explore the consequences for other areas of high energy astrophysics. We will focus on the connection between UHECRs and neutrinos [2] and investigate the possibility for detecting the neutrinos associated with the UHECR acceleration in AGNs. From the experimental point of view the detection of UHE diffuse and point source neutrinos in the  $\text{km}^3$  IceCube detector is promising [3] and the AMANDA collaboration has already reported interesting limits [4].

Roughly 10 events are concentrated in the Centaurus direction, a region with a high density of AGNs, constituting a hot spot in the Auger UHECR map. Our focus will be on Centaurus A (Cen A) as a case study (see also [5]). Two events fall near this galaxy, suggesting that it could be the first identified UHECR source. Indeed, Cen A, the nearest AGN at a distance of only  $\sim 4$  Mpc [6], has long been considered as a prime UHECR source candidate [7]. The problem of predicting the neutrino flux from Cen A is similar to the attempts to relate the observed UHECRs diffuse flux with a prediction, or at least with an upper bound, for the diffuse UHE neutrino flux [8, 9, 10]. We will employ basically the same approach for the case of Cen A with the help of the available data on its spectral distribution. Various models of neutrino emission from AGNs have been discussed in the past (see for example [11]). A recent update has been considered in [12, 13]. We describe our model in more detail below.

## I. THE AUGER FLUX

The expected number of events in the Auger array can be calculated starting from the total integrated exposure. The Auger group reports  $\Xi = 9000 \text{ km}^2 \text{ yr sr}$  at present [1]. For point sources we need the exposure per steradian given by  $\Xi/\Omega_{60}$  where  $\Omega_{60} = \pi \text{ sr}$  is the Auger field of view corresponding to 60 degrees as maximum zenith angle. In addition the relative exposure  $\omega(\delta)$  is required, weighting a source with declination  $\delta$  for the effective observation time.  $\omega(\delta)$  is parameterized according to [14] using  $\theta = -35^\circ$  for the Auger declination and normalizing to 1 the maximum. Assuming a power law shape for the energy spectrum  $F = F_0(E/E_0)^{-\alpha}$  we get

$$N = F_0 \frac{\Xi \omega(\delta_s) E_0}{\Omega_{60} (\alpha - 1)} \left( \frac{E_c}{E_0} \right)^{1-\alpha} \quad (1)$$

where  $E_c$  is the threshold energy, or, equivalently

$$F = \frac{N \Omega_{60} (\alpha - 1)}{\Xi \omega(\delta_s) E_0} \left( \frac{E_c}{E_0} \right)^{\alpha-1} \left( \frac{E}{E_0} \right)^{-\alpha}. \quad (2)$$

For the case of Cen A we have  $N = 2$  events above a threshold  $E_c = 60$  EeV with a source declination  $\delta_s \simeq -47^\circ$  and relative exposure  $\omega(\delta_s) \simeq 0.64$  which gives

$$F \simeq 1.95 \left( \frac{E}{\text{EeV}} \right)^{-2.7} \frac{1}{\text{km}^2 \text{ yr EeV}} \quad (3)$$

or  $E^3 F \simeq 6 \times 10^{22} (E/\text{EeV})^{0.3} \text{ eV}^2/\text{m}^2 \text{ s}$ . The uncertainty on the flux estimate is roughly  $\sqrt{2}/2 \sim 70\%$  from Poisson statistics. The intrinsic slope with just two events is very uncertain and we thus use  $\alpha = 2.7$  as seen in the diffuse UHECR flux just before the GZK cutoff assuming it as generally representative of the typical UHECR emitter. The uncertainty in the Cen A flux is therefore significant, but the situation is expected to improve as more statistics is collected by the Auger array allowing, in principle, to constrain the spectral index directly from the data. Further, once the source is

clearly identified, also lower energy events can be used to reconstruct the spectrum, despite the larger magnetic deflections. We will see in the following, however, that the main source of uncertainty in the  $\nu$  flux is the AGN modeling rather than the UHECR flux uncertainty. An additional uncertainty is related to the possible systematic error on the absolute energy scale of Auger of up to 30%. An independent calibration is in principle possible exploiting the dip feature present in the UHECR spectrum at  $\sim 10^{18}$  eV [15]. This gives  $E_c = 80$  EeV and a flux roughly a factor  $\sim 1.6$  higher. Below we refer to this as the “dip” energy scale.

Dropping the factor  $\Omega_{60}/\omega(\delta_s)$  we can use Eq. (2) also to estimate the diffuse UHE flux. Using  $N$ ,  $E_c$ ,  $\Xi$  from [16] we find  $F \simeq 21 (E/\text{EeV})^{-2.7} 1/\text{km}^2 \text{ yr sr EeV}$  or  $E^3 F \simeq 2 \times 10^{24} (E/\text{EeV})^{0.3} \text{ eV}^2/\text{m}^2 \text{ s sr}$ , in good agreement with the Auger estimate itself [16].

## II. AGN MODELING AND $\nu$ FLUX

To relate the expected neutrino flux to the observed CR flux several assumptions and an underlying model are unavoidably required. The usual scenario assumes that protons are shock-accelerated to ultra-high energies and then interact with ambient radiation or matter producing secondary neutrons and pions with an associated flux of gammas and neutrinos. If we assume that protons are magnetically confined in the source so that only neutrons can escape producing the observed flux of UHECRs, a direct link between neutrinos and UHECRs, or more generally an upper limit, is possible [8, 9, 10]. In the following we will use this hypothesis. The presence of particles accelerated up to  $10^{20}$  eV indeed implies a magnetic field generally strong enough to confine the particles themselves. Furthermore, even if the protons can finally diffuse out of the source, the acceleration region is generally expanding so that adiabatic losses limit the maximum attainable energies [25].

UHE protons can interact in the source both with matter through  $p + p \rightarrow p(n) + \pi s$  or with the local radiation field through  $p + \gamma \rightarrow p(n) + \pi^{0(+)}$ . Subsequent pion decay then produces photons and neutrinos. The collisionless conditions required for efficient shock-acceleration imply a relatively low matter density so that at ultra-high energies the dominant neutrino production channel is generally the photo-hadronic one. We will thus focus on this process, using the Monte Carlo code SOPHIA [18] to simulate the interactions of protons in the Cen A radiation field and to normalize the relative yields and multiplicities of the secondary particles per interaction. These processes occur mainly close to threshold and produce only 1-2 pions per interaction.  $p$ - $p$  interactions, instead, although disfavored, have quite higher ( $\gtrsim 10$ ) pions multiplicities [17] and thus would also give higher neutrino multiplicities. Finally, we will neglect muons and pions synchrotron losses in the source MF that however are expected to affect the  $\nu$  flux only at the highest energies

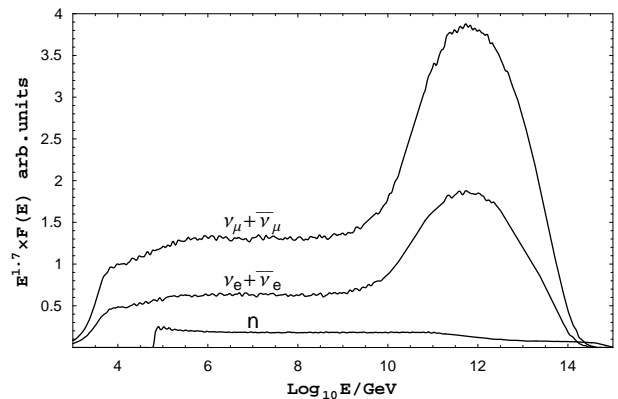


FIG. 1: Resulting neutron,  $\nu_\mu + \bar{\nu}_\mu$  and  $\nu_e + \bar{\nu}_e$  spectra for an  $E^{-1.7}$  and  $10^5 < E/\text{GeV} < 10^{15}$  proton injection spectrum interacting on the photon field of Cen A simulated with SOPHIA in the optically thin source limit.

(see [13, 19] for a throughout discussion on the role of MFs).

The final neutrino yield has also a dependence on the Spectral Energy Distribution (SED) of the Cen A radiation field. In particular, if numerous enough ambient high-energy (x-ray/gamma) photons and thus high CM energies are available, in principle the multi-pion production channels can be activated and an higher neutrino multiplicity per interaction can be achieved with respect to the expected low near-threshold yield. We consider especially  $\nu$  production in the nucleus for which detailed SED information is available. The jet case is more uncertain and will be discussed briefly. A compilation of measurements of the Cen A nucleus is reported in [20]. The SED has an approximate double peak structure with an infrared peak and a second soft-gamma peak. Upper limits in the TeV region at the level of few % of the Crab flux has been reported by the current generation of VHE cherenkov telescopes [21, 22]. We adopt for the photon number density the crude approximation of a broken power law  $n(\epsilon) \propto \epsilon^{-1.9}$  over the range  $0.001 \text{ eV} < \epsilon < 100 \text{ MeV}$  and  $n(\epsilon) \propto \text{const.}$  for  $\epsilon < 0.001 \text{ eV}$ , accurate enough to determine the actual neutrino production regime. We show in Fig. 1 the resulting neutron and neutrino spectra for an  $E^{-1.7}$  proton injection spectrum interacting on the photon field of Cen A simulated with SOPHIA in the optically thin source limit, in which multiple proton-photon interactions have a negligible role. Indeed, it can be seen from the figure that the interactions occur near threshold for the whole relevant energy range, while only at very high, unimportant, energies  $E_\nu > 10^{10} \text{ GeV}$  we enter in the higher neutrino production regime. We therefore use the relevant average quantities valid in the  $E_\nu < 10^{10} \text{ GeV}$  range, namely:  $\langle \xi_\nu \rangle \simeq 0.1$ ,  $\langle \xi_n \rangle \simeq 0.5$ , as the fraction of proton energy transferred respectively to the neutrino ( $\nu_e + \nu_\mu$  + their antiparticles) and neutron component per interaction, and  $\eta_{\nu n} = \langle E_\nu \rangle / \langle E_n \rangle \simeq 0.04$  for the average neutrino to neutron energy. The final neutron and

neutrino flux are thus simply related via

$$F_\nu(E) = \frac{\langle \xi_\nu \rangle}{\langle \xi_n \rangle \eta_{\nu n}^2} F_n(E/\eta_{\nu n}) \quad (4)$$

where the factor  $\langle \xi_\nu \rangle / \langle \xi_n \rangle \eta_{\nu n} \simeq 5$  gives the average mean neutrino/neutron multiplicity. Notice that the multiplicity is  $> 3$  implying that, even near threshold, more than one pion is on average produced per interaction. Our estimates are in fair agreement with ref. [18] to which we address the reader for a more detailed discussion of the various neutrino production regimes in photo-hadronic processes.

If, on the other hand, the production site is located in the Cen A jet rather than in the nucleus, a softer, more x-ray populated,  $n(\epsilon)$  photon spectrum can be possible [23] and an higher neutrino multiplicity is achievable. However, in this case the site of acceleration would be the shock regions/hot spots in the jet, where a large scattering in the spectral indexes is observed [23] so that a firm prediction is hard to establish. We also remark that Cen A is classified as a misaligned BL Lac with its jet pointing  $20^\circ$ - $40^\circ$ [24] away from our line of sight so that the relativistic boosting effect should not play a major role if the UHECRs come from the jet.

To extrapolate the neutrino flux from the CR flux to PeV energies further modeling of the internal acceleration mechanism of the source is required. Extrapolating the  $E^{-2.7}$  spectrum to very low energies is clearly unrealistic and in fact several breaks in the slope of the energy spectrum with subsequent steepening as the energy increases are predicted. We follow [10, 25] for the modeling of these breaks in the neutron spectrum and to relate it to the observed UHECRs spectrum. We thus consider a scenario in which an ambient proton spectrum  $\propto E_p^{-1.7}$  interacts with the low energy radiation field producing neutrons that, escaping from the source, decay into the observed CRs spectrum. The proton injection index 1.7 is in general agreement with the typical value  $\approx 2$  expected from shock acceleration and it is chosen in such a way that the CR spectral index matches the value 2.7 at Ultra High energies (see below). Although the details are generally quite model dependent two clear breaks are predicted in neutron/CR spectrum in the highest energy regime. In the first the spectrum steepens by one power when the pion production process becomes efficient while a second one power steepening is predicted when the source becomes optically thick to photo-hadronic interactions. The two breaks are generally close so we assume a single break at the energy  $E_b$ . The resulting UHECR spectrum is then

$$F_{\text{CR}}(E) \propto \begin{cases} E_b^{-2} E^{-0.7} & (E < E_b), \\ E^{-2.7} & (E > E_b). \end{cases} \quad (5)$$

There are thus three species in the model with different energy spectra: underlying, not directly observable protons, with an injection spectrum  $\propto E_p^{-1.7}$ , photo-produced underlying neutrons, with a spectrum  $\propto E_n^{-0.7}$

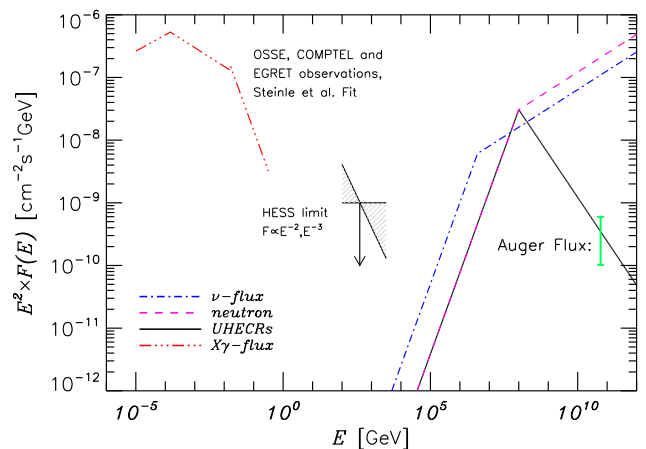


FIG. 2: Final neutron, UHECRs and total neutrino spectrum in the model of this work, normalized to the Auger observation at  $E \simeq 60$  EeV. Also shown is the fit to the MeV soft-gamma observations [26, 27] and the HESS upper limit around  $\sim 1$  TeV [21]. The Cen A UHE- $\gamma$  curve, not shown for clarity, lies close to the neutrino curve.

before the break and  $\propto E_n^{-1.7}$  after the break thus following the proton spectrum, and escaping “physical” neutrons, with spectrum further showing one power steepening above the break,  $\propto E_{\text{CR}}^{-2.7}$ . The escaping neutrons then decay back into protons far from the source constituting the final CR spectrum whose UHE tail is observed in Auger. The various nuclear species spectra and the neutrino flux are shown in Fig. 2. The proton injection flux is not shown for clarity. Notice that the neutrino spectrum is in general supposed to follow the *underlying*, neutron spectrum via Eq.(4), i.e. unattenuated by pion losses and with a behavior  $\propto E^{-1.7}$  above the break energy. We will see however that the final expected rate of neutrinos is insensitive to the exact behavior of the spectrum above the break. It also does not depend crucially on the slope below the break as long as it remains in the range between 1-2. The main parameter determining the neutrino rate is the actual break energy itself. To estimate this we use observations of the gamma spectrum from Cen A.

The most important point to take into account to this aim is that gamma photons interact via pair production with the same low energy photon background relevant to the photo-hadronic interactions so that a break in the gamma spectrum can be related to a break in the UHECR spectrum. In particular, considering the ratio of the related cross sections and inelasticities it can be seen that [9, 10]  $\tau_{n\gamma}(E_n)/\tau_{\gamma\gamma}(E_\gamma) \simeq 4 \times 10^{-9} E_n/E_\gamma$ , where  $\tau_i$  is the optical depth of the related process. When the source becomes optically thick to both processes (i.e.  $\tau_{n\gamma} = \tau_{\gamma\gamma} = 1$ ) we thus have the relation  $E_{b\gamma} \simeq 4 \times 10^{-9} E_{bn}$  between the neutron and gamma break energies. Thus, differently from the determination of the neutrino multiplicity, the exact shape of the spectrum is in this case crucial. Cen A observations in the

gamma band [26, 27, 28] show several breaks in the range 100 keV-100 MeV with a photon spectral index  $\alpha \simeq 1.7$  for  $E \lesssim 200$  keV and  $\alpha \simeq 3.0$  for  $10 \lesssim E \lesssim 100$  MeV [26]. The exact energy of the highest break, however, is time dependent due to the intrinsic variability of the source. Further, the observations become photon limited above 200 MeV [28], making unclear if a further relevant spectral steepening is present above this energy. To be conservative we assume a gamma break at the highest detected energy bin found by EGRET at  $E_{b\gamma} \simeq 200$  MeV, implying  $E_{bn} \sim 10^8$  GeV. Anyway, given the importance of this parameter, that basically determines the normalization of the neutrino flux, in the following we also analyze the effect of a different choice for  $E_{bn}$ . We show in Fig.2 our final neutrino, neutron and UHECR spectra together with a fit to the MeV soft-gamma observations [26, 27] and the HESS upper limit around  $\sim 1$  TeV [21].

We finally comment on the hadronic associated gamma flux expected to accompany the CR and neutrino fluxes (see also ref. [29] for a specific analysis of the issue). The  $\langle \xi_\gamma \rangle$  and  $\eta_{\gamma n}$  factors are indeed very similar to the neutrino case so that the neutrino and gamma fluxes are predicted to be very close in shape and normalization. However, while neutrinos leave the sources just after production, gammas are subject to further processing through the development of an electro-magnetic cascade that depletes the high energy photon tail producing sub-TeV photons. Pair production in the low energy photon field of the source and electron synchrotron losses need thus to be taken into account for a prediction of the observable gamma flux. This, in turn, require further modeling of the source adding further uncertainties in the predictions.

### III. EVENT RATE IN A NEUTRINO TELESCOPE

Pion decay yields the flavor ratio  $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ . However, due to oscillations, we expect the ratio  $\nu_e : \nu_\mu : \nu_\tau = 1 : 1 : 1$  at Earth. At energies  $E_\nu \gtrsim 100$  TeV, neutrino telescopes are fully efficient both to tracks from charged current generated  $\mu$ 's and to showers from  $\nu_e$  events.  $\tau$  leptons from  $\nu_\tau$  interactions are expected to be detected both as showers near  $E = 100$  TeV and as tracks in the higher energy range. For southern hemisphere detectors, like IceCube, neutrino events from Cen A are down-going. In particular, Cen A, with a declination  $\delta \simeq -47^\circ$  appears at a zenith angle of  $43^\circ$  in the IceCube field of view.

Regarding the background, for  $E_\nu \gtrsim 100$  TeV the atmospheric neutrino flux is negligible while the residual background of atmospheric muons has a quite steep spectrum rapidly decreasing with energy. For simplicity we assume full efficiency for UHE neutrino detection, while a more careful evaluation would require a detailed Monte Carlo simulation. The final background is thus constituted by the UHE diffuse  $\nu$ -flux itself whose relevance is linked to the detector angular resolution which at these

$E_c$	$E_b = 10^7$ GeV	$E_b = 10^8$ GeV	$E_b = 10^9$ GeV
60 EeV	6.7 yr <sup>-1</sup>	0.35 yr <sup>-1</sup>	0.016 yr <sup>-1</sup>
80 EeV	11.0 yr <sup>-1</sup>	0.56 yr <sup>-1</sup>	0.026 yr <sup>-1</sup>

TABLE I: Cen A event rate in IceCube for various break energies  $E_b$  and for the Auger and “dip” energy scales.

energies is  $\sim$  few degrees [3]. We will limit ourselves to estimate the expected  $\nu$ -flux while assessing the corresponding statistical significance will eventually rely on the measured diffuse flux normalization. To calculate the event rate in a km<sup>3</sup> detector like IceCube we assume for showers an effective volume of  $V_{\text{eff}} = 2$  km<sup>3</sup>. For track events the effective volume could be much higher due to the muon and tau range. However, for a zenith angle of  $43^\circ$  the available overburden is limited. We therefore conservatively use the same  $V_{\text{eff}}$  also for tracks. From the effective volume the expected event rate is

$$\mathcal{N} = N_A \rho V_{\text{eff}} \int_{E_{\text{th}}}^{+\infty} dE_\nu \sigma_{\nu N}^{CC} F_\nu(E_\nu) \quad (6)$$

where  $N_A$  is the avogadro number,  $\rho$  the density of the target material (ice in this case),  $E_{\text{th}} = 100$  TeV is the threshold energy and  $\sigma_{\nu N}^{CC} = 6.78 \times 10^{-35} (E_\nu/\text{TeV})^{0.363}$  cm<sup>2</sup> is the CC cross section [30].

Using the neutrino flux from the previous section, gives  $\mathcal{N} \simeq 0.35$  yr<sup>-1</sup> or  $\mathcal{N} \simeq 0.56$  yr<sup>-1</sup> for the dip calibrated energy. Thus the conclusion is that IceCube should collect  $\mathcal{O}(\text{few})$  events from Cen A in 5 years. This could be enough for a confident detection of the source if the diffuse UHE  $\nu$ -background is not too high. However, although the detection of Cen A may be challenging we can in principle extend the analysis to the whole Auger hot spot assuming that the related UHECRs emitters share the characteristics of Cen A. This results in a rate  $\mathcal{N} \simeq 2$  yr<sup>-1</sup> in a region of radius about 10 degrees centered on Cen A which should be evident after a few years of observations. As anticipated the estimated event rate does not depend crucially on the neutrino flux slope while it is very sensitive to the break energy,  $E_b$ , which determines the relation between the neutrino normalization and the UHECR normalization as inferred from Auger. In Table I we show the scatter in the values of  $\mathcal{N}$  for different values of  $E_b$  and for the Auger and “dip” energy scales. An order of magnitude variation in  $\mathcal{N}$  is in principle possible if the value of  $E_b$  differs correspondingly by one order of magnitude. Clearly further observations in the gamma band would be desirable to have a more robust estimate of  $E_b$ . Fortunately the situation is expected to improve with the launch of the GLAST satellite that should provide high quality data up to GeV energies and possibly beyond. Also, deeper observations from Cherenkov telescopes in the TeV range would contribute to improve the picture.

Despite the uncertainties the prospect of neutrino detection from Cen A and its surroundings are quite promising with the exciting possibility to perform true



multi-messenger astronomy, observing for the first time a source in UHECRs, neutrinos and  $\gamma$ -rays. This would also allow for detailed studies of the source acceleration mechanism [31] and, if flavor tagging can be achieved, neutrino exotic properties could be tested [19, 32].

We conclude by commenting on a puzzling aspect of the Auger data [33]: Although many AGNs lie in the direction of the Virgo cluster, no events are detected. Al-

though the statistics is low and this could be an exposure effect it is intriguing to notice that the issue can be settled by observations of the associated neutrino emission in IceCube.

*Acknowledgments* — We thank F. Halzen, P. D. Serpico and G. Miele for valuable comments on the manuscript. Use of the publicly available SOPHIA [18] code is acknowledged.

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